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Final Report

**HIGH SPEED ELECTRONICALLY TUNABLE
FIBER-OPTIC-FILTER**

CLIN/SLIN: 0001AC

February 20, 2006

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THE FINAL REPORT

FOR

“HIGH SPEED ELECTRONICALLY TUNABLE FIBER-OPTIC-FILTER”

SUBMITTED 20 FEBRUARY, 2006

FINAL PROGRAM STATUS REPORT: ☒ YES NO

REPORTING PERIOD: 26 August, 2005 through 20 February, 2006

SUBMITTED TO: U.S. NAVAL AIR SYSTEM COMMAND

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PREPARED UNDER: CONTRACT NUMBER N00014-05-M-0260

The undersigned representative states that he/she has prepared the following information and that the facts and data set forth are completed and accurate to the best of the undersigned’s knowledge and belief. Questions regarding this report to should be addressed to Kevin Ryu of the Subrecipient’s organization at (818-737-7799, kryu@sabeus.com).


Contractor name Sabeus Photonics

Signature _____

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Date 20 February, 2006

REPORT DOCUMENTATION PAGE					Form Approved OMB No. 0704-0188	
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</p>						
1. REPORT DATE (DD-MM-YYYY) 20-02-2006		2. REPORT TYPE The final report		3. DATES COVERED (From - To) Aug 2005-Feb 2006		
4. TITLE AND SUBTITLE High Speed Electronically Tunable Fiber-Optic Filter				5a. CONTRACT NUMBER N00014-05-M-0260		
				5b. GRANT NUMBER		
				5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Ryu, Kevin, H.				5d. PROJECT NUMBER		
				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Sabeus Inc. 26610 Agoura Road, Suite 100 Calabasas, CA 91302				8. PERFORMING ORGANIZATION REPORT NUMBER STTR N00014-05-M-0260-FR-001		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research 875 North Randolph Street, Suite 1425 Arlington, VA 22203-1995				10. SPONSOR/MONITOR'S ACRONYM(S) ONR		
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) 0001AC		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT <p>During phase I, two main areas of the tunable filter were investigated intensively. The first and the most important subject was increasing the tunability of the LPG based filter device in order to enable tuning over the required wavelength range (>50nm, in C-band). The second was how to create a tunable filter device with acceptable strength and narrow bandwidth for 100 GHz DWDM applications. Tunability over a range of 50 nm was successfully demonstrated during this period with the parallel configuration with electro-optic polymer composites containing nanosized ZnS crystallites. For fabricating filter device, the direct writing of the LPG through the etched optical fiber with ITO layer coated was successfully achieved. This technique eliminates the several critical uncertainties such as peak shifting coming due to chemical etching of the fibers and the peak shifting resulting from the ITO coating. Together with this approach, considerable effort was made to determine the optimal conditions of LPG writing (such as the grating period, grating length and cladding layer thickness) to yield a strong stable spectral transmission peak in the C-band.</p>						
15. SUBJECT TERMS Tunable Fiber-Optic Filter, Long Period Grating, Electro-optic Polymer						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT	b. ABSTRACT	c. THIS PAGE			Ryu, Kevin H.	
U	U	U	UU	12	19b. TELEPHONE NUMBER (Include area code) 818-737-7799	

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1. SUMMARY


This report outlines the major accomplishments made during Phase I of the “**HIGH SPEED ELECTRONICALLY TUNABLE FIBER-OPTIC-FILTER**” program from August 20th, 2005 to February 20th, 2006.

During phase I, two main areas of the tunable filter were investigated intensively. The first and the most important subject was increasing the tunability of the Long Period Grating (LPG)-based filter device in order to enable tuning over the required wavelength range (>50 nm, including the C-band). The second was how to create a tunable filter device with acceptable strength and narrow bandwidth for 100 GHz DWDM applications.

Tunability over a range of 50 nm was successfully demonstrated during this period with the parallel configuration (sandwich structure) with Electro-Optic (EO) polymer. The concentric cylindrical configuration, however, is expected to yield wider tunability compared to the parallel configuration. With much empirical data from the study on the effect of matching index of Electro-Optic (EO) polymer, we were able to predict and control the optical properties of EO polymer composites containing nanosized ZnS crystallites successfully.

Decreasing the bandwidth of the devices while maintaining sufficient resonant peak strength required significant theoretical modeling and fabrication processes development. Several important results gleaned from theoretical modeling and empirical observations indicated that the original fabrication approach would not yield adequate devices because of unexpected shifting and weakening of the as-written resonant peak strength in the transmission spectrum within the C-band. These changes were due to the etching of the fiber cladding layer. In addition, the effects of the ITO (Indium Tin Oxide, internal electrode layer) were not originally considered in the modeling because of its extremely thin dimension (~50 nm). In order to explain the originally unanticipated changes in the spectrum these unexpected effects, detailed analysis, starting from the simplest model toward complicated multi-layered model were employed. Based on this theoretical modeling, several different approaches for fabricating the LPGs are now being evaluated. The most promising fabrication process, which was developed after the second progress report submitted, is a direct writing of the LPG through the etched optical fiber with ITO layer coated. This technique eliminates the several critical uncertainties such as peak shifting coming due to the chemical etching of the fibers and the peak shifting resulting from the ITO coating. Together with this approach, considerable effort was made to determine the optimal conditions of LPG writing (such as the grating period, grating length and cladding layer thickness) to yield a strong stable spectral transmission notch in the C-band.

Sabeus also undertook an effort to demonstrate the feasibility of creating narrow bandwidth resonant peaks (less than 5 nm at -3dB) on LPG technology for this tunable filter application. Sabeus successfully demonstrated this capability by writing a strong resonant peak with 2.5 nm at -3dB Full-Width at Half-Maximum (FWHM) after modification of the hardware and software in one of the Sabeus' LPG production stations at Freeport, Pennsylvania. Additionally, Sabeus investigated the use of sol-gel technology an alternative fabrication method for applying the internal ITO electrode to the fiber. The tooling for the sol-gel dip coating and heat treating process was designed and built.

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2. TECHNICAL ACHIEVEMENTS

2.1. Development of a quantitative four layer model

The basic configuration of the tunable filter is a thin ($\sim 35 \mu\text{m}$ diameter) cladding, long period fiber grating (LPG) with an additional, variable refractive index secondary cladding layer made of electro-optic polymer. By varying the refractive index of the polymer via an applied electric field, the resonant transmission notch in the LPG transmission spectrum could be tuned over a range of wavelengths. In order to apply an electric field across the polymer, a thin layer of ITO is deposited on the LPG. The polymer and a gold electrode are subsequently deposited on the polymer.

Based on this configuration, a quantitative 3-layer model was used to determine the LPG parameters (e.g., cladding thickness and grating period) required for a large turning range ($> 50 \text{ nm}$). The 3-layer model was so named because it considered the refractive indices of the fiber core, the fiber cladding, and the electro-optic polymer cladding. The model neglected the ITO layer because its thickness ($\sim 50 \text{ nm}$). However, during the course of this work, Sabeus and PSU determined that the ITO (which has an index of ~ 1.8 for sputtering conditions used for its deposition) had a significant effect on both the tunability and the resonant notch depth of the LPG. Literature supporting these findings was discovered, as well. As a result, a new 4-layer model was developed that included the refractive index and thickness of the ITO layer.

The 4-layer models and reference literature provided a better understanding of the effects that were observed experimentally. The tunability and depth of the LPG were affected by the high index ITO because of mode transitioning, as reported in the literature “Mode transition in high refractive index coated long period gratings” by A. Cusano et al.¹ With a high index overlay, cladding modes transition out of the cladding as the refractive index of the ambient medium increases. Prior to this work, Ignacio Del Villar² showed that the deposition of an overlay of higher refractive index (up to $n=1.67$) than the cladding layer in an LPG increases the sensitivity to ambient refractive index changes.

According to A. Caruso et al.¹, when a lower order mode transitions out of the cladding, the adjacent higher order mode moves into vacancy left by the vacating mode. The ambient index at which the modes transition is a function of the overlay thickness and the overlay refractive index. Figure 1 shows the mode transitions for several different thicknesses of such an overlay. As each mode transitions out of the cladding, the overlap between the cladding mode and the core mode decreases, resulting in a decrease in the coupling coefficient between the core mode and the given cladding mode as shown in Figure 2. This reduction in the coupling coefficient manifests itself in the form of reduced notch depth in the optical spectrum of the LPG.

¹ A. Cusano, A. Iadicicco, P. Pilla, L. Contessa, S. Campopiano, and A. Cutolo, “Mode transition in high refractive index coated long period gratings” pp. 19-34, Vol. 14, No. 1, Optics Express (2006).

² I. Del Villar, I. R. Matias, F. J. Arregui and P. Lalanne, “Optimization of sensitivity in long period fiber gratings with overlay deposition” pp. 56-69, Vol. 13, No. 1, Optics Express (2005).

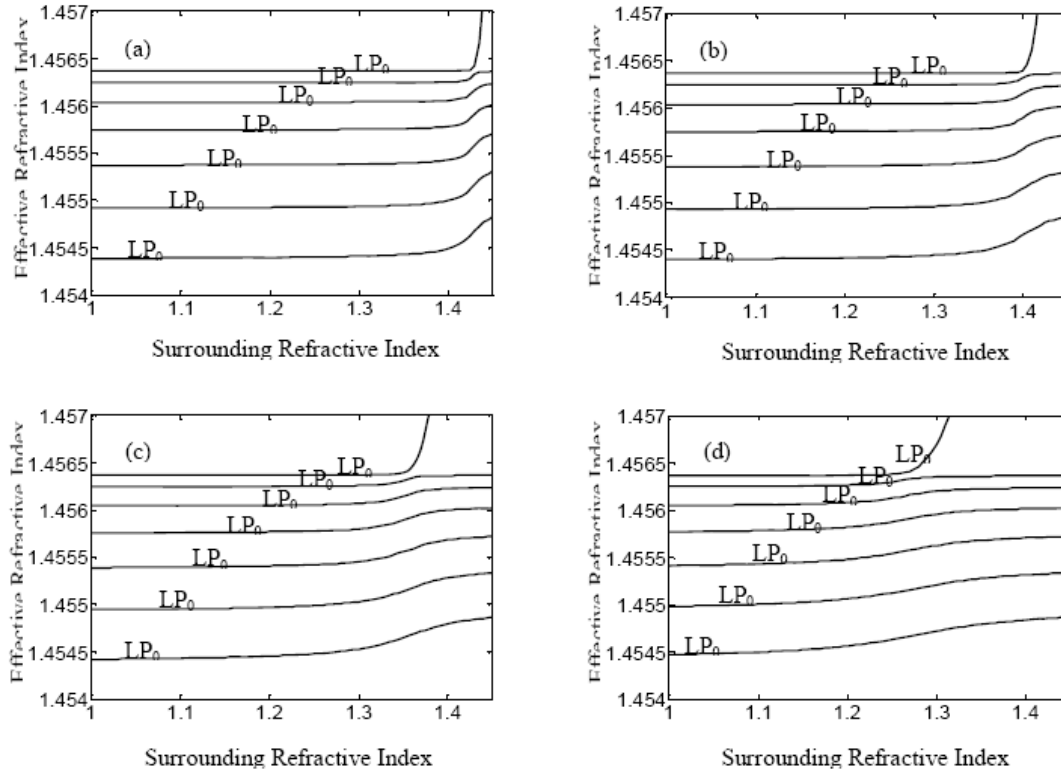


Figure 1. Effective refractive index of the LP_{02} - LP_{08} cladding modes versus the surrounding refractive index in a high refractive index ($n = 1.578$) coated LPG with (a) 150 nm thin film, (b) 200 nm thin film, (c) 250 nm thin film, (d) 300 nm thin film. (Cusano et al¹).

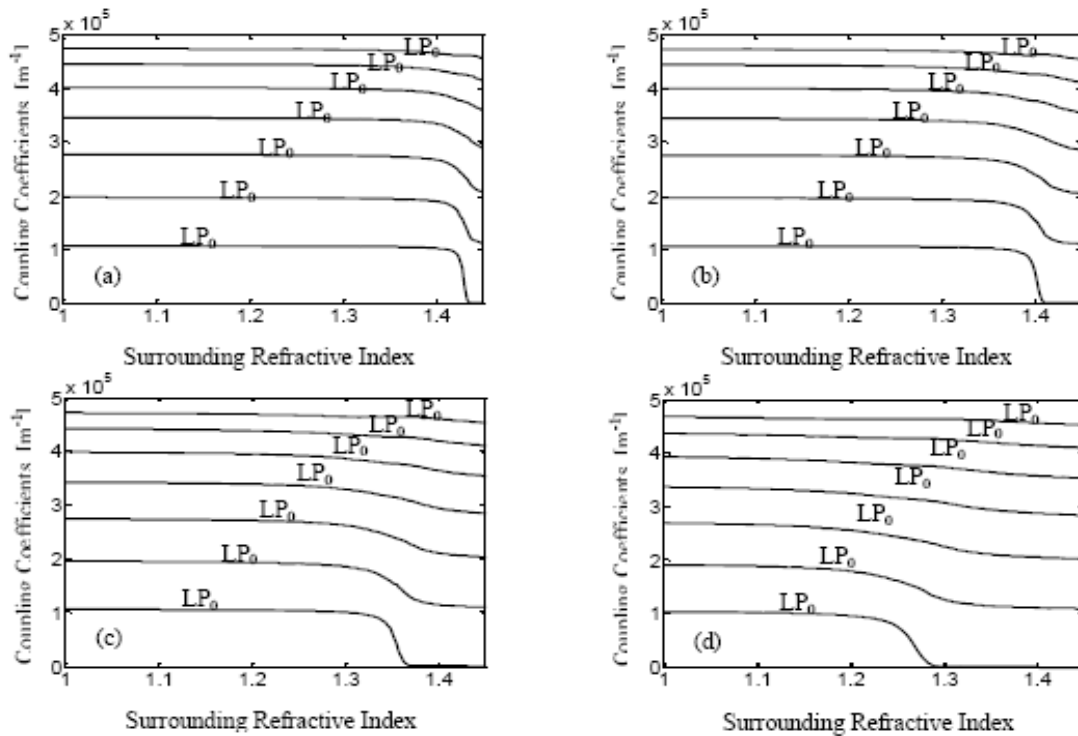


Figure 2. Coupling coefficients of the LP₀₂ - LP₀₈ cladding modes versus the surrounding refractive index in a high refractive index ($n = 1.578$) coated LPG with (a) 150 nm thin film, (b) 200 nm thin film, (c) 250 nm thin film, (d) 300 nm thin film. (Cusano et al¹.)

From Figure 1, we see that the effective index of the lowest order cladding changes rapidly as it the transitions occur more easily. While this high sensitivity is desirable for a wide tuning range, Figure 2 shows that a severe drop in the coupling constant accompanies this effective index sensitivity. As a result, the first cladding mode may not be the best candidate for tuning. While the effective indices of the higher order modes may not be as sensitive, their coupling constants do not deteriorate in as sensitive a manner, providing for a much stronger peak in the LPG spectrum.

These results provided insight into how to plan to additional research and development in fabricating the device. By specifying thickness of the ITO and the indices of the ITO and polymer layers, fabricating LPGs whose higher order mode transitions occur in the index range of the electro-optic polymer is a likely method for optimization. This method will maximize both tunability and notch depth.

2.2. Experimental demonstration of tunability range greater than 40 nm

As explained in section 2.1, the overlayer with higher refractive index material like Indium Tin Oxide (ITO) makes an LPG sensitive to even small refractive index changes in the next layer such as the EO polymer. The original approach to make a tunable filter device was writing LPG first within the photosensitive fiber ($\sim 125 \mu\text{m}$ diameter), and then etch the cladding to a diameter of $\sim 35 \mu\text{m}$ chemically. After etching, the ITO layer was deposited by physical vapor deposition (PVD) on the surface of the fiber as an inner electrode. As discussed in the previous section, the thin ITO layer significantly changed the notch wavelength and its strength. Several approaches were made to avoid this sensitivity. One of the approaches was to write the LPG after finishing all the fabrication steps except the final step of deposition of outer electrode. If this approach succeeded, it would provide a significant advantage for the fabrication of the tunable filter because there would be no further changes in the resonant peak wavelength and strength compared to the original approach of writing, etching and adding successive layers. The modified approach required to write LPG through the ITO and EO polymer layers. This approach failed due to burning, caused by local heating of the EO polymer by the UV laser radiation used to write the grating. Only with weak power of UV laser and extremely long exposure time might be able to write LPG thru the EO polymer layer even with the burning of the polymer. This approach will be inefficient in manufacturing devices due to slow speed of writing LPG. Also, long exposure periods have the additional disadvantage, that there may be some mechanical drift and hysteresis that add to imperfections in the LPG.

A second approach of writing the LPG through only the ITO layer was successful. For example, one device was prepared by etching the cladding to a diameter of $43 \mu\text{m}$ and coating with a $\sim 50 \text{ nm}$ layer of ITO. Then, an LPG was written through the ITO layer and tested by immersion in different index matching solutions. The result shown in Figure 3 confirmed the sensitivity of the resonant notch position according to the slight change in ambient refractive index as explained by Ignacio Del Villar et al². In Figure 3, the resonant notch was shifted almost 30 nm by the index change of 0.014 in the index matching fluid. This result also suggests that optimizing the refractive index range in EO polymer will lead to a useful device.

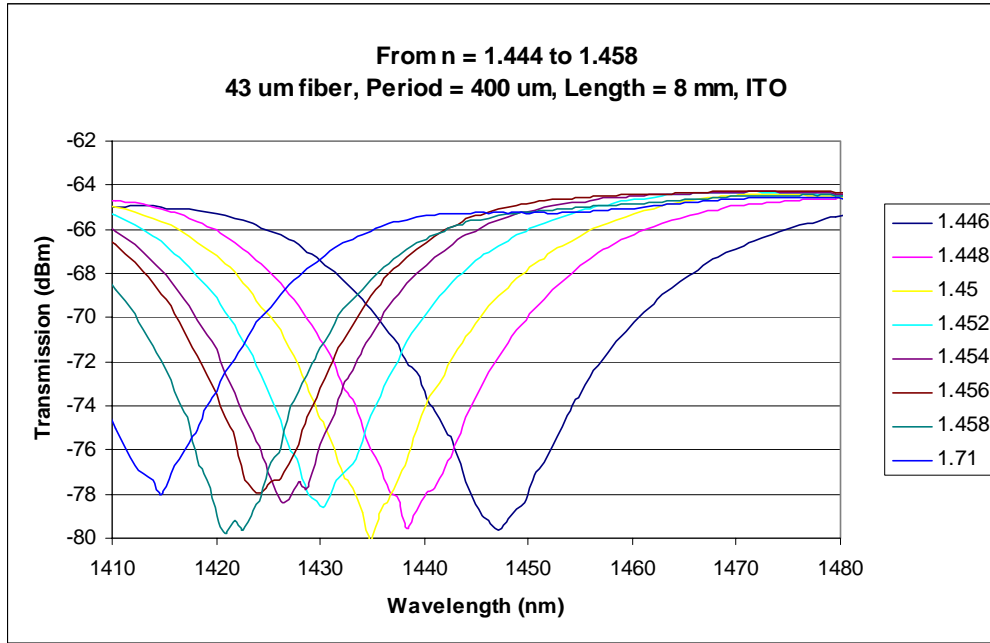


Figure 3. The shifting of the resonant peak versus ambient refractive index with a device written through the ITO layer.

Figure 4 is the spectrum of the widest tunability LPG fabricated by the Sabeus and PSI team to date. The figure shows a tuning range greater than 50 nm, but the notch depth is only constant (± 0.5 dB) over about 40 nm. These plots also illustrate the mode transitioning effect. Notice that at 0 V, there is no discernible peak, but as the voltage increases (i.e. polymer index increases) the notch starts to form change with voltage. Once the LPG parameters are better optimized, the depth is expected to remain constant over the entire tuning range. The bandwidth of this particular sample was wide, an issue that will be addressed in the next section.

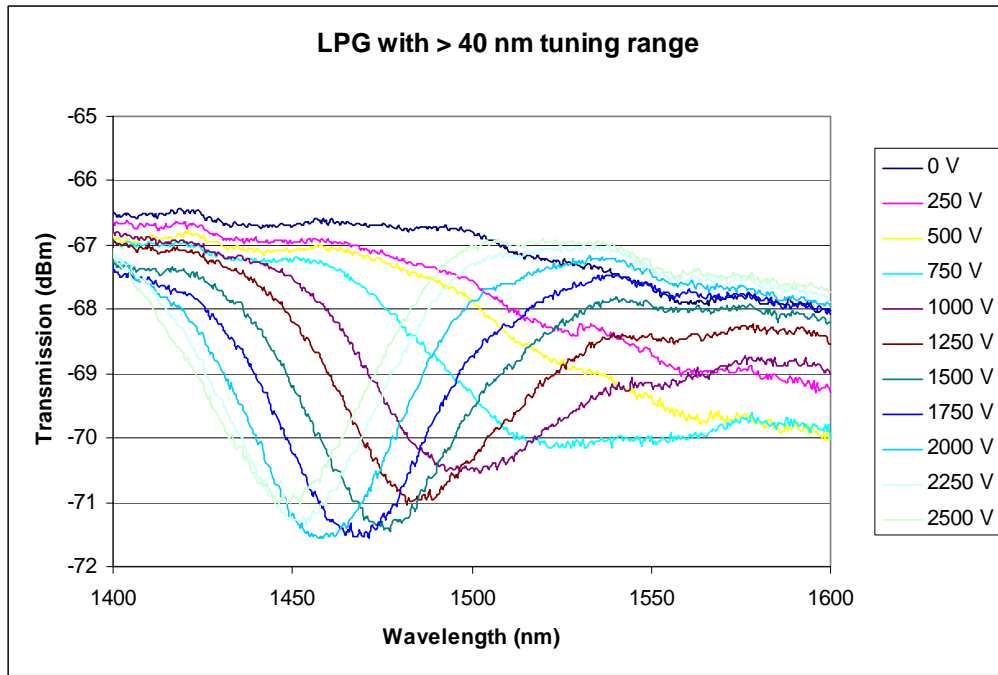


Figure 4. Experimental data from LPG with > 40 nm tuning range.

3. OTHER MISCELLANEOUS EFFORTS

3.1. Fabrication and Demonstration of Narrower Bandwidth at FWHM with New Sabeus' Long Period Gratings

One of the fundamental requirements for optical tunable filter for 100GHz DWDM applications is to have a filtering resolution under 0.8 nm for each channel. The current resolution target for LPGs used in this Phase I program is 5 nm at FWHM. In the first progress report, the simulation results showing the relationship between the length of LPG and the bandwidth at FWHM was presented. Based upon our simulation results, less than a nanometer of bandwidth at FWHM can be obtained with a half meter long LPG using grating period of 216.5 μm . However, it was desirable to verify the prediction experimentally.

Sabeus designed and modified the hardware of an existing LPG fabrication station to write a longer length LPG in order to prove that significantly narrower bandwidth filters were achievable, per the modeling results. A 10-inch long (~ 25 cm) LPG with 216.5 μm grating period was targeted as an experimental goal for proving the feasibility of creating a narrower bandwidth (2.5 nm) LPG. To allow for the stitching technique for writing the LPG (point to point), the full range of available mechanical motion of the writing stage was increased to approximately 15 inches (enough to fabricate the narrower bandwidth resonant notch) and the operational software was upgraded to enable control of the longer mechanical motion of the stage. Five LPGs were made with lengths of 10 inches. All the transmission spectra showed resonant notches with ~ 2.5 -3 nm bandwidth and depths of 15-21dB. As shown in Figure 5(a) and (b), the empirical results matched well to the simulation results (2.5 nm FWHM).

Conclusively, the simulation and empirical results confirmed the feasibility of fabricating LPGs with a resonant peak less than 1 nm FWHM simply by increasing the physical length of the LPG.

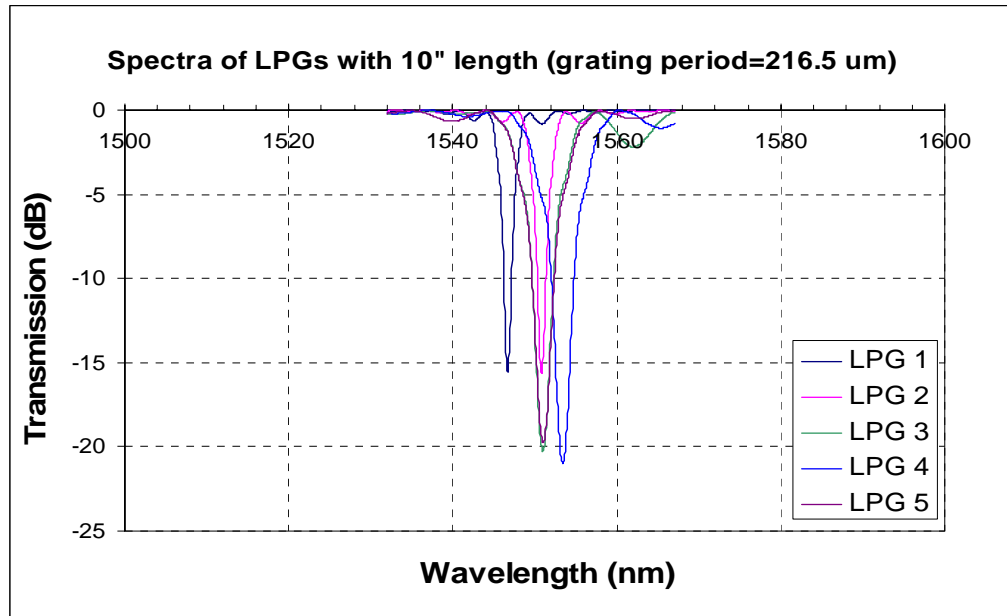


Figure 5-(a). Spectra for 5 devices

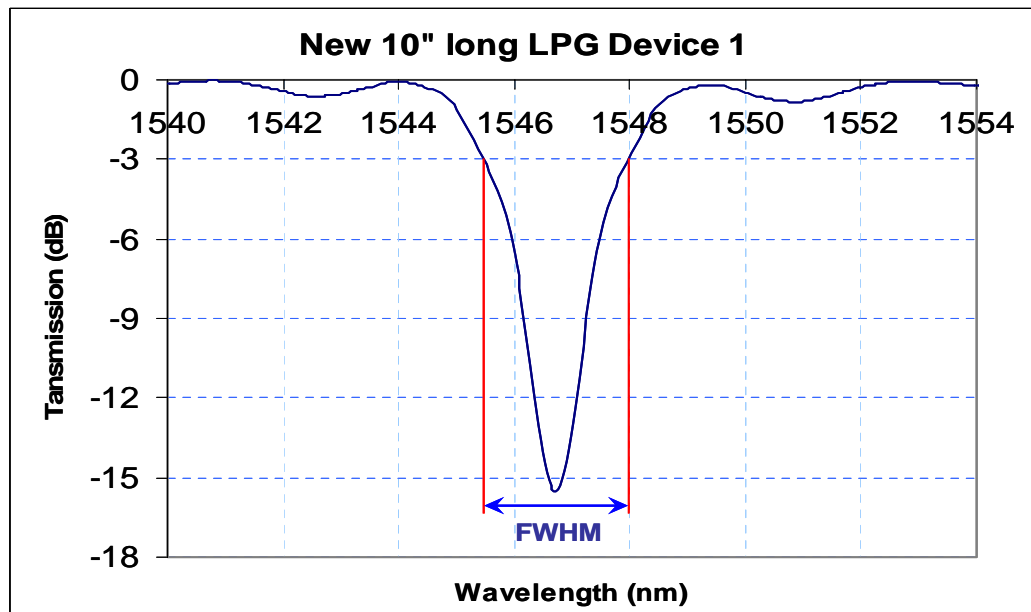


Figure 5-(b). Detailed spectrum of device No. 1

Figure 5. 2.5 nm bandwidth at -3 dB (FWHM) in 10-inch long New Sabeus' LPG

3.2. Dip Coater for Sol-Gel application of ITO film deposition

The present method of ITO application is RF sputtering onto a heated substrate. The process is long (many hours for pumpdown and deposition), and it is difficult to achieve adequate circumferential

uniformity in the coating thickness. Additionally, most affordable coaters are limited to substrate lengths of a few inches. Sol-gel technology was chosen to be investigated as an alternative fabricating method for applying the internal ITO electrode to the fiber. Dip coating is a practical application method, and would be very useful as a batch processing technique for forming the ITO layer on the cladding surface. Very recently, the hardware of the dip coater setup was completed as shown in Figure 6, and the software for precise stepper motor control was coded. This coater is designed to deposit the ITO on the fiber over lengths of up to a half meter (0.5 m). Completion of the process requires subsequent heating the coating to remove the solvent from the ITO.

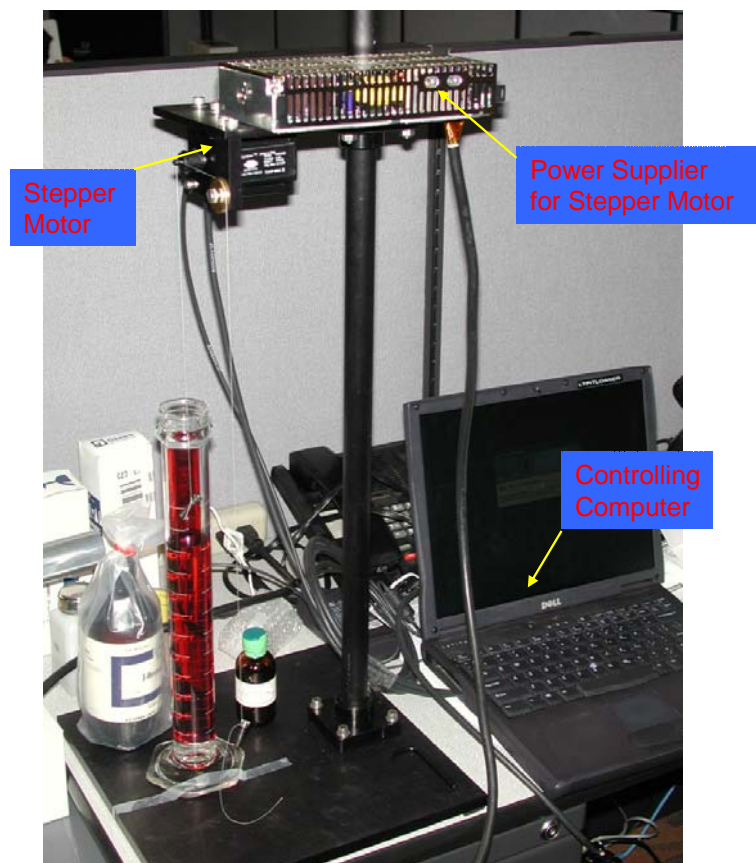



Figure 6. Dip coater for Sol-Gel method of ITO deposition

4. CONCLUSION

During Phase I period, several issues were identified, investigated and resolved that provided the Sabeus team with the ability to reliably model and predict the performance of the LPG tunable filter technology. It is now clear that writing an LPG filter on 125 μm , then etching to 35 μm dramatically shifts the absorption (resonant) peak. This effect has been modeled, quantified, and validated. In addition, the strength and center wavelength of the LPG was shown to be very sensitive to the final etched dimension (fiber diameter). This was also modeled and validated. Consequently, a new etching process was specified to achieve the required diameter tolerance. More recently, Sabeus and PSU independently developed multi-layer models that include all filter layers that show excellent correlation,

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thus can be used in the future as design tools. Also demonstrated during this reporting period was the ability to tune an LPG filter over a 50 nm range, and a clear path to achieving a 1 nm bandwidth filter based upon increasing the physical length of the LPG.

Recently, the new approach to write LPG through the ITO layer was proved to be successful. Based on the theoretical modeling and literatures, the overlay with higher refractive index like ITO ($n \sim 1.8$) heavily affects to the coupling mode between the core and the cladding layers as well as the responding of the resonant peak to the ambient layers like EO polymers. The success of the new approach is able to eliminate the uncertainties in final shifted position and the strength of the resonant peak in LPG. Now, the optimization of the LPG writing conditions over the ITO layer in order to make a resonant peak narrower and stronger is critically necessary as well as of the EO polymers including precise refractive index control and uniform application methodology.